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Fourth Semi-Annual Report

A Fundamental and Feasibility Study of Ring-Vortex Gaseous-Core Cavity Reactor

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I. Introduction

This is the fourth semi-annual report (August 1, 1965 to January 31, 1966). During the last two years, from February 1, 1964, to January 31, 1966, research work has been carried out in the Department of Space Science and Applied Physics, Catholic University of America on the feasibility study of gaseous core cavity reactor under the Grant NsG 586. The initial phase of the effort is mainly concentrated on exploring and understanding the fluid mechanical aspects on the feasible models of the cavity reactor which are initiated in the Space Propulsion Laboratory of the Department.

In order to improve the specific impulse of the feasible gas core reactor over that of the solid core reactor, mobile fuel elements are desirable and may undergo the material states of solid, liquid, gas and/or plasma according to level of temperature of the reactor, through the operating cycles from start to stop and to restart again. Therefore for simulation in the model study during the last two years, light gas or liquid has been used as propellent fluid with solid particles, heavy liquid or gas as the mobile fuel elements. The immediate problems are on (a) to confine the mobile fuel elements orderly and steadily in all the material states in the model, (b) how to minimize the fuel loss from drifting away by the fast moving propellent fluid in exhaust and (c) how to determine the flow characteristics.

Two types of reactor models are studied (1) cylindrical geometry and (2) toroidal geometry. A large number of two-dimensional models with different designs, injection and exhaust schemes have been studied and compared, before the promising three-dimensional models are chosen.

(1) Cylindrical Geometry

In the cylindrical geometry, the preliminary study is concentrated in the following three main areas with liquid as propellent combined with heavy liquid or solid particles as fuel.

(i) Good containment of heavy fuel elements at starting and stop under gravitation. It is found that a considerable amount of mobile fuel elements can be drifted away easily by the exhausting propellent in the process of start and stop. To prevent this type of fuel loss, a great deal of study is made on the optimum shape of the end portion of the model.

(ii) Effect of end tangential jets on fuel distribution and containment. The secondary flow which is developed both next to the cylindrical wall and end walls can lead to substantial fuel loss. Some end tangential jets are arranged to control the amount of axial fuel distribution, thus minimizing the fuel loss.

(iii) Control of radial location of fuel distribution. The fuel elements can be pushed away from the wall against centrifugal force. This is done by varying the amount of the radial injection of propellent fluid. This may be considered as a means of fuel confinement without overheating the wall.

(iv) Velocity and pressure measurements. Wall static pressure distribution has been measured in a number of cases. Because of being three-dimensional turbulent rotational motion, the measurements of local particle velocity either of propellent or fuel elements in the flow field are difficult and some new techniques are in development. Some preliminary results are included in Appendix A.

With the progress on finding some promising cylindrical models from the above study and experience, we are planning to build a number of better and more accurate models in the third year program to carry out a higher degree of measurements and evaluations on the feasible models. Our understanding of the fluid mechanics of these models will thereby be improved.

(2) Toroidal Geometry

It is a very complex problem to study in the model of the toroidal geometry because it is difficult to observe visually. As sound preparatory steps, a large number of two-dimensional models have been studied prior to construction of the first three-dimensional model.

(i) Two-dimensional circular model of tangential injection and outlet. For the case of the density ratio $\frac{\rho_2 - \rho_1}{\rho_1} << 1$, the heavy fluid with density ρ_2 can maintain at the center core with very little loss and is driven as a solid body by the high speed light fluid of density ρ_1 injected along the circumference wall. The containment seems favorable. However, in the case of $\frac{\rho_2 - \rho_1}{\rho_1}$ being large or much larger than unity, the high density fluid cannot maintain at the central core but diffuse toward the wall under the influence of the centrifugal force through rotation. The containment of heavy fluid is not good. The situation on containment can be improved greatly by withdrawing the light fluid from a mouth of the outlet tube located near the core. There is difficulty in determining the concentration of heavy gas with the present gas chromotograph, because of its low sensitivity. Some laser light observation technique is under development. The experimental system is in the process of construction. The rented laser will be delivered in the next few weeks.

The containment of solid particles mixed in liquid or in gas has been observed to be exceedingly good, particularly with suction mouth of the outlet tube located near the core center. Currently, the containment of heavy gas in light gas is under study.

(ii) Propellent Exhaust Outlet. A great deal of study has been made to improve the propellent exhaust outlet such that the least amount of fuel elements can be drifted away by the exhausting propellent. The withdrawing mouth as stated in (i) is found very effective. Some preliminary experimental data are shown in Appendix B.

(iii) Three-dimensional Model. A three-dimensional model is developed and is made with stainless steel shell of 6 1/2 inches minor diameter and 2 1/2 feet overall diameter with glass windows through which the fuel particle motion can be observed under a special light system. Preliminary runs with compressed air, sand and glass beads seem to show excellent containment of fuel elements. Mixture of heavy and light gas will be studied in the third year.

(3) Theoretical Study

A. General Theoretical Approach

In this program when any new experimental phenomena is discovered, a discussion among members of the whole group is immediately held which usually stimulates some new ideas and physical insight into a problem. Then some simplified mathematical model can be formulated and mathematical treatment will start. In other words, we try to develop some simple theories first to fit the needs of the experiments.

In the present program, two phase fluid flow of high density ratio is essential to the problem. Three-dimensional configuration, radial and circumferential drifts, secondary flow, centrifugal force, mass transfer, heat transfer, magnetohydrodynamic effects, instability and bouyance force all are also very important features in the present stage of study. However, each of the above features is a difficult subject to analyze in fluid mechanics and heat transfer, particularly with turbulent multiple-species flow. Because of the complexity of the problem, both useful experimental and theoretical results cannot be achieved in a short time. Better understanding can only be gained through many careful experiments, intelligent observations and measurements, and timely needed analysis.

B. Stability Study

A study of the stability of a swirling flow in a circular magnetic field has been made and the stability criterion is established. A rather striking phenomenon is that there is a case in which the unstable circulatory flow field is counterbalanced by the unstable circular magnetic field such that the combined field makes a stable flow. The general analysis and detailed calculations are contained in Technical Report No. 65-006.

(a) "The Stability of Swirling Flow of a Viscous Conducting Fluid in the Presence of a Circular Magnetic Field," by Hsien Ping Pao, Technical Report No. 65-006, (SSAP), May, 1965. A sufficient condition for the stability of a swirling flow in a circular magnetic field is established. A stronger sufficient condition for stability is also given on physical grounds and by an approximate mathematical proof. Detailed results for small spacing between the cylinders are given. It is shown that the stronger sufficient condition for stability is exact for small spacings. A new branch of solution which corresponds to negative critical Taylor number is calculated.

An approximate solution for a particular case is also given. A rather striking phenomenon is that there is a case which the unstable circulatory flow is counterbalanced by the unstable circular magnetic field such that the combined field makes a stable flow. The dual roles of viscosity and magnetic diffusivity and their physical mechanism are also discussed.

(b) "The Stability of Viscous Conducting Swirling Flow in the Presence of a Circular Magnetic Field and a Radial Density Gradient," by Hsien Ping Pao, SSAP Technical Report, The Catholic University of America. (In preparation).

Due to some difficulties encountered in the numerical calculations, the final form of this report has not been completed. The stability of an electrically and thermally conducting swirling flow in the presence of a radial temperature gradient, as well as a circular magnetic field is studied. New classes of solutions which correspond to the negative generalized Taylor number are calculated and tabulated. The interesting conjugate relationship between different branches of solutions is revealed. The roles of three diffusive coefficients, momentum, magnetic, and thermal diffusivities, are discussed.

(c) "Magnetohydrodynamic Flows of Rotating Fluids," by Hsien Ping Pao, SSAP Technical Report, partly supported by NASA Grant NsG 586 (in preparation).

In this work, two cases are being considered·

(1) Rotating flows of Von Karman (rotating disk).

(2) Rotating flows of Bodewadt (fixed disk), both in the presence of a circular magnetic field. The governing equations have been reduced to a set of ordinary differential equations by the similarity argument. Some numerical calculations are being carried out. It is found that the circular magnetic field has a stabilizing effect upon the rotating flows. The interaction is quite significant when the magnetic Prandtl number ν/η is large or the magnetic field strength is strong. The flow also exhibits the boundary layer nature as does the non-magnetic case.

(d) "Taylor Instability of a Jet in a Stratified Gas Flow," This work will be presented in SSAP Report No. 66-002 by Dr. T. J. Eisler and will be submitted in the middle of February. In the cavity reactor a hot heavy gas is supported by a lighter cool one. While the system is, of course, unstable, the temperature distribution may give rise to a stratification of density or entropy which is stable within each layer. The stability with respect to small perturbations of such a configuration has been studied assuming an incompressible, inviscid fluid and a velocity profile of the jet type. The cominant instability is associated with the density discontinuity (Taylor instability) and is largest for large values of the wavenumber of the perturbation (small eddies) in which case it is essentially decoupled from other effects. It is found that for small wavenumbers the effect of the stable stratification is de-stabilizing.

C. Density Profile and Suction in Mixed Flow

(a) Continued study on the establishment of density profile for the flow of a two-fluid single phase gas mixture has been undertaken. A theory is developed for the case of swirling flow with the body force provided by the centrifugal action of the swirl. Solutions are given for a large class of swirling motions including motions with reverse flow. Asymptotic forms of the density profiles are explicitly calculated. A "singular" perturbation scheme is used to give the orders of the higher order correction terms in terms of the reciprocal of a diffusive Reynolds number, and the uniform valicity of the zeroth order solution is established. The first report 65-005(a) was published as NASA Cr-330 and the second report will also be published as NASA Cr and is now in print. The work is done by Dr. T. W. Kao.

Study is also being made on the theoretical determination of the composition of the fluid withdrawn from the cavity reactor to assess what is the percentage of fuel that is lost if the concentration profile of the fuel is established according to the theory mentioned in the last paragraph.

Previous investigations on the establishment of concentration profiles have assumed the flow to be inviscid and essentially incompressible. The effects of viscosity and compressibility have therefore to be assessed. It is also desirable to incorporate injection and withdrawal into the problem. Presently, a two-dimensional cylindrical axi-symmetric model with prescribed tangential and radial velosity at the outer radius and withdrawal from an inner radius is being considered for a binary, viscous, compressible fluid.

D. Radiation Heat Transfer Between Two Parallel Streams of Optically Thick Flows

The radiation heat transfer between two parallel streams of absorbing and emitting radiating gases is studied. The problem is described by the Rosseland diffusion approximation together with the radiation slip boundary condition. Considering that the flow is incompressible and inviscid, the exact solution of the problem is obtained. The solution shows a smooth transition regime between the optically thin and the optically thick regions. The thickness of radiation layers is calculated. The report on this work (No. 66-001) is prepared by Dr. Y. C. Whang and has been sent out at the end of January 1966.

(4) Publications and Lecture

During the two years interval, eight reports have been/will be sent to the Office of Grants and Research Contracts, NASA. A lecture on Experimental Development of Gas Core Reactor at Catholic University was given by Dr. C. C. Chang to the Lewis Research Center, NASA, on November 22, 1965.

The reports are shown in the following list:

Technical Rept. No. (SSAP)	Title	Date Submitted
65-001	Stability of Two-Layer Viscous Stratified Flow Down an Inclined Plane	2/4/65
65-002	Magnetohydrodynamic Boundary Layer Between Parallel Streams of Different Magnetic Fields and Temperatures	2/4/65
65-003	Stability of a Shear Flow in an Unstable Layer	2/4/65
65-005(a)	On the Establishment of Density Profile for the Flow of a Two-Fluid Single Phase Gas Mixture (published as NASA CR-330)	4/9/65

Technical Reports (cont'd)

65-005(b)	Establishment of Concentration Profiles for a Binary Fluid for Duct and Swirl Flow	6/18/65
65-006	The Stability of Swirling Flow of a Viscous Conducting Fluid in the Presence of a Circular Magnetic Field	6/18/65
66-001	Radiative Transfer for Parallel Streams of Radiating Gases	2/1/66
66-002	Stability of a Jet in a Stratified Gas Flow	2/1/66

According to Mr. R. G. Ragsdale of Lewis Research Center, Reports 65-002 and 65-005 will be published at Lewis and further distribution will be made from there. Report No. 65-006 also was submitted to the Journal of Physics of Fluids for publication. Report No. 65-001 is already published in the May 1965 issue of Journal of Physics of Fluids. Report No. 65-002 also has been submitted to the AIAA Journal for publication and is in revision.

In the next few months, a number of reports will be completed and forwarded to the Office of Grants and Research Contracts, NASA. Some of the details of these reports will be stated in this progress report.

APPENDIX A. Preliminary Measured Data of Cylindrical Geometry

As mentioned in our previous reports that confinement of heavy particles in fluid medium is extremely well for this geometry. Studies were made on internal cavity design, flow characteristics, confinement of different density ratio solid particles, liquid to liquid and gas to gas phases. Some preliminary results are presented in the following:

1. Experiment with flow of liquid :

(A) Test Model Geometry: (refer to Figure 1.)

Cylinder of 6 1/2" I.D.

Length = 11 1/2" , L/D = 1.75

Two tangential jets, one on top end wall one on bottom end wall with same right hand sense of rotation looking from the top. One 1 1/4" exhaust opening at the center of bottom of cylinder.

(B) Trapping of heavy solid particles in light fluid medium: Water

Heavy particles	Specific Gravity	Particle Size
sand	1.8	20 - 60 mesh
glass beads	2.5	1/32" - 1/16" Ø
lead shots	11.3	.005 - .030" Ø
iron powder	7.5	100 - 1000 microns

When the unit is operating with top of bottom jets balanced at approximately 1:1 flow ratio, at a radial Reynolds No. about 140 ($Re_r = \rho Q/2\pi L\mu$) corresponding to a flow rate of 4 GPM and particle tangential velocity along the wall = 2.5 ft/sec., the various solid particles listed above, could all be completely trapped in a circular ring in the mid-section of the cylindrical cavity. Due to the conical design feature of the lower end wall, these heavy solid particles originally settled at the outer periphery of the bottom end wall surface, will be swept away by the bottom jet upward, picking up speed instantly and its centrifugal force off-sets the radial inward pressure gradient produced by outer vortex flow. Thus no particle will be carried away by the radial boundary layer mass flow at the end walls toward exhaust. This characteristic makes possible the complete trapping of heavy particles during normal running condition as well as during intermittent stopping and re-starting operations.

(C) Pressure Distribution, Velocity Distribution, and Flow Pattern of Cylindrical Geometry

a. Pressure distribution:

Study of static pressure distribution curve plotted from measured data showed a clear and well defined relationship between the position of trapped particles with the static pressure distribution along the axial direction of the cavity. Refer to Figure II and III, evidently the particles were trapped in the low pressure region between the two swirling jets on opposite ends, and kept away from center core through the action of centrifugal force. When the top jet is shut off, with only the bottom jet in operation, lowest pressure (axial direction) will be found near the top end wall and all the heavy particles will be forced toward this region, their weight supported by the axial pressure gradient. Radial pressure distribution is indicated in Fig. IV. Measurement was taken from the top end wall.

b. Velocity distribution:

Tangential velocity distribution, (refer to Fig. V.) of the cavity may be obtained through the use of tracers synchronizing with straboscope and camera shutter. The velocity profile is close to theoretical potential vortex flow (conservation of circulation) at outer radius $V \propto 1/r$ but deviates appreciably when it approaches the core. When radial flow is introduced at the center section to force the heavy particles away from the side-wall at the later part of the experiment, tangential velocity distribution is further modified as can be seen from Fig. V. Radial and axial velocity is difficult to determine as multiple cell flow pattern exits throughout the cavity the velocity profile varies along the axial direction of the cavity so that axial symmetry no longer exits. Maximum axial velocity is found at the outer periphery of the center vortex core.

Flow pattern:

Observations of flow pattern were made with tracer dye injection at various locations. Solid tracer with density approximate to water were also used. A strong axial down-flow region from the upper end wall boundary layer to the exit hole in the lower end wall, its diameter is approximately equal to the exit hole diameter at bottom end wall; an annular upflow region surrounding it. Another somewhat diffused downflow region surrounds both of them. However, outside of this core structure, other cells of circulation were also present. New fluid admitted through the jets first circulates along the walls to achieve the effect of cooling, then enters into local up and down cell motion and finally exits through the center core. Sufficient residence time is ensured for heat transfer processes.

A portion of new fluid admitted tends to short-circuit toward exhaust through the radial boundary layer mass flow at the end walls. This boundary layer mass flow is affected by the design of end wall contours. A proper end wall contour will set up local up-and-down cell motion to reduce this boundary layer flow. An optimum design and its effectiveness has yet to be determined.

(D) Liquid to liquid

While setting the model cavity in normal operation top and bottom jets balanced, dyed carbon-tetrachloride (sp.gr. 1.58) liquid was injected into the flow. The heavy non-miscible-with-water liquid would disperse into liquid droplets behaving like heavy solid particle forming a ring of droplets trapped in the mid-section of the cavity.

(E) Addition of Radial Flow

The cylindrical model was modified by perforating the section of side wall, where the ring of heavy particles suspended, with holes (1/16 dia holes at 1/4" spacing). An external jacket was added so that water may be forced through the perforated holes in radial direction to force the particles away from side wall. This is necessary for reactor operation so that solid walls will not be overheated by fuel elements. This radial flow seemed to be effective in forcing the particles toward the core in a distributed sheet. Due to jet action of these small perforated holes, the particles bounded back and forth along the sidewall and flow was quite turbulent. Radial velocity is high in this section, resulting short flow residence time. Its effect to tangential velocity distribution is shown in Fig. V. The purpose of forcing the heavy particles away from side wall is partly achieved but too turbulent to be of practical value to gaseous flow condition where loss of fuel due to turbulent diffusion would be high. Radial flow in the midsection by introducing tangential jets at this section seems to be more desirable. Although the particles cannot be forced away at some distance from the sidewall yet the layer of cool laminar flow interposing between the fuel element and side wall would be highly desirable. More reliable results will have to be determined from gas to gas phase models.

II. <u>Experiments with Gas-Flow Medium</u>

A. Trapping of heavy particles in light fluid medium

Flowing fluid medium: Helium gas (mol. wt. 4)

Heavy particles: sand particles

iron powder

When the unit of Fig. I is operating with top and bottom jets balanced at approximately 1:1 flow ratio, at a radial Reynolds number above 20 ($Re_r = \rho Q/2\pi L\mu$) corresponding to a flow rate of 10 SCFM with jet speed 450 ft/sec. The heavy solid particles listed above could be completely trapped in a circular ring in the mid-section of the straight cylindrical cavity. The flow characteristic is essentially the same as liquid medium model as in the previous experiments.

B. Trapping of Heavy gas in light gas medium:

Continuous-flow light fluid medium -- Helium (Mol. Wt. 4)
Heavy gas used: Freon-12 CCl_2F_2 (Mol. wt. 120)

Experimental Model used:

Model # / (Refer to Fig. I)

Equipment used:

Gas Chromatograph

Perkin Elmer Model 820

Honeywell Viscorder Model 906C

When the unit is operating at a Radial Reynold No. 32 with top and bottom jets balanced as in the previous experiment corresponding to pure Helium flow rate of 16 SCFM with jet speed 720 ft/sec. A limited amount of pure Freon gas ($\sim$ 100 cc) is injected either into the helium inlet jet or directly into the mid-section of the cylinder. Consecutive extractions of mixture at sampling port located where the band of heavy freon exits, are immediately taken by a 2 cc syringe 30 seconds after completion of injection. These sampling mixtures are fed directly into the gas chromatograph to obtain freon concentration readings from the Honeywell viscorder. The decay of freon concentration with time is similar to Fig. VII in Appendix B. Very encouraging results are obtained as concentration decreases approximately 50% (by volume) every minute while the total quantity of helium flow per minute is 60 volumes of cylinder capacity. Turbulent diffusion seems to be the main cause of loss of freon concentration. This containment could definitely be improved with better cavity configuration and careful jet design. A study of flow pattern for this model with water and dye injection will help to achieve better design and cut down turbulence in the cavity.

Further study of this model with addition of radial flow to force heavy gas away from side wall needs to be made, in consideration of wall overheating problems. Other quantitative measurement techniques are being developed to determine accurately the amount of freon being trapped, the discharge volumetric or weight flow ratio between freon and helium, etc.

APPENDIX B. Preliminary Experimental Data for Toroidal Geometry

Toroidal Geometry

A 6-in. cross-sectional diameter stainless steel 3-dimensional model was fabricated with two diametrically opposite exhaust ports and four tangential injection ports spaced equally. The injection ports could be tilted to provide axial velocity to the vortex ring core. The exhaust ports have adjustable stem insertions into the cavity so that selective withdrawal of fluid mixture at different radial positions can be achieved. In the meantime, the streamlined exhaust stem may be rotated in relation to the flow direction to cause minimum turbulence. Cross-sectional flow pattern may be viewed through viewing ports with slit light incorporated; however, overall view of heavy particle for fluid movement is difficult to obtain. A two-dimensional model made of acrylic clear plastic is used to study the effect of exhaust port stem insertion with regard to heavy fluid containment and its radial concentration distribution. Since toroidal geometry does not have end-walls, no solid particle or heavy fluid will escape through the radial mass flow due to end-wall boundary layer interaction, therefore, the same end-wall design and jet arrangement that we have developed for our cylindrical geometry is used to achieve this simulation. This two-dimensional model will only give one narrow band of trapped heavy fluid or particle while in the toroidal geometry, the distribution of heavy particle or fluid will be more-or-less uniform along the entire wall. Never the less, for our present study of exhaust port effect and radial concentration distribution, this should prove satisfactory.

Referring to Fig. VI, a band of heavy particles (and or iron particles) are trapped near the center of the two-dimensional model. The location of this trapped heavy-particle band can be shifted at will by adjusting the two end wall gas jet relative strength. The heavy particles are travelling along the side wall with concentration distribution conforming roughly to what is illustrated in Fig. VI.

From measured data of heavy gas freon concentration in continuous flow of light helium gas, the distribution of heavy freon is very much similar both longitudinally and radially to that of powdered heavy particles.

When the band of heavy particles is shifted (by adjusting the end jets) to sampling port #1 location which is directly under the exhaust port location, the effect of exhaust port stem insertion can readily be determined. The desired length of insertion for selective withdrawal of fluid mixture depends on the operating speed of the unit. Higher operating speed (i.e., higher gas flow rate) tends to compress the heavy particles or heavy gas into a thin band or layer against the side wall, leaving the center portion with very low concentration. The effect is entirely due to centrifugal force, so that only short insertion length is necessary. At relative high speed operation an insertion length = 1/5 D (D = Dia.) of cavity cross-section prove to be satisfactory. Short insertion is desirable so that cooling exhaust port stem would not be a problem in actual case. Low speed operation needs longer stem insertion. But for gas operation, high operating speed means higher turbulence level and turbulent diffusion is the main cause of loss of heavy fuel element; therefore, an optimum high speed has to be determined which depends on the physical aspects of the cavity construction and design.

To determine the loss of heavy freon gas due to turbulent diffusion for this geometry, some concentration measurement data are presented in Fig. VII. Concentration readings were taken at sampling port #2 where the band of heavy gas was adjusted to locate. The decay of trapped freon concentration seems to be quite slow considering the large flow rate of light helium gas.

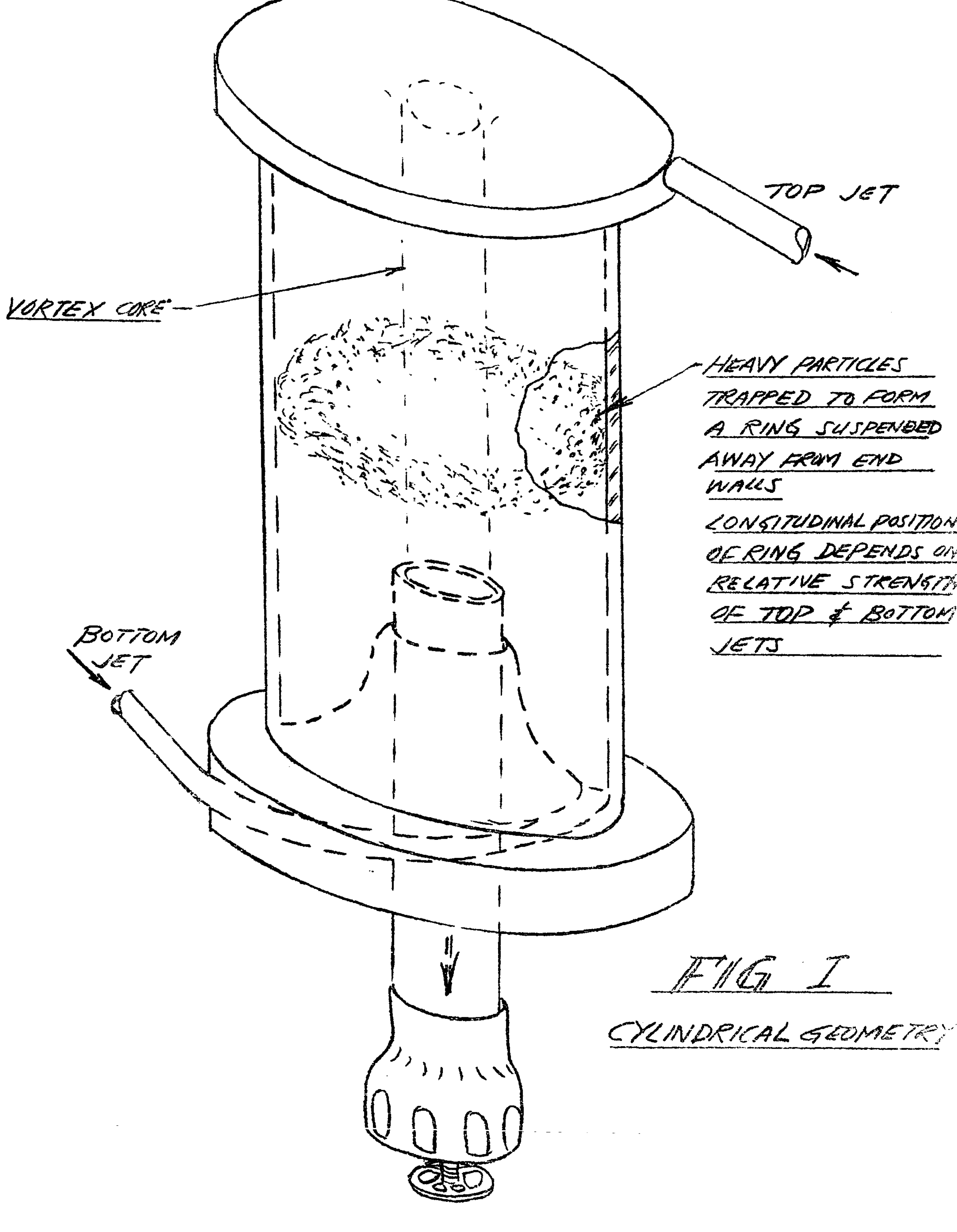
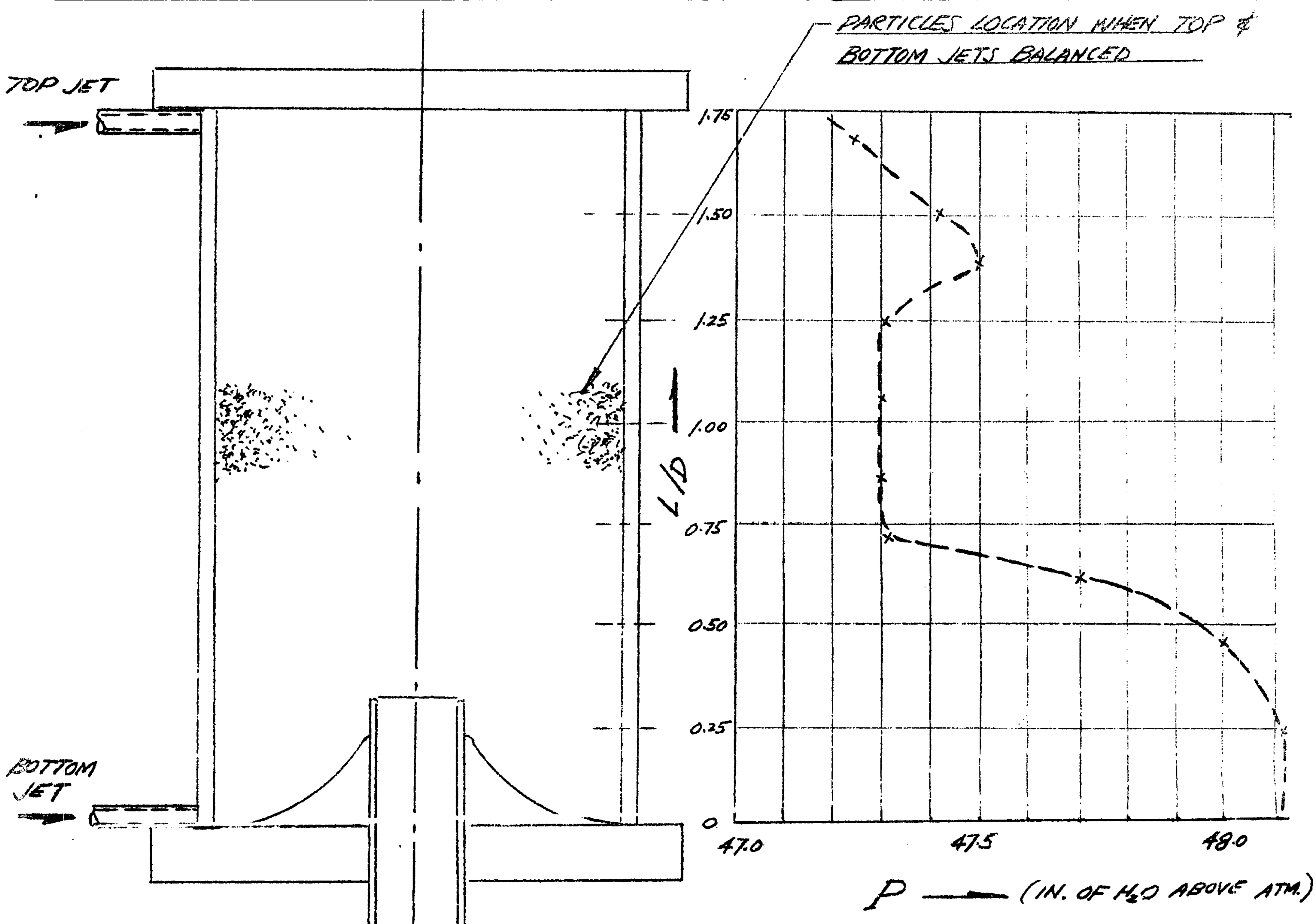


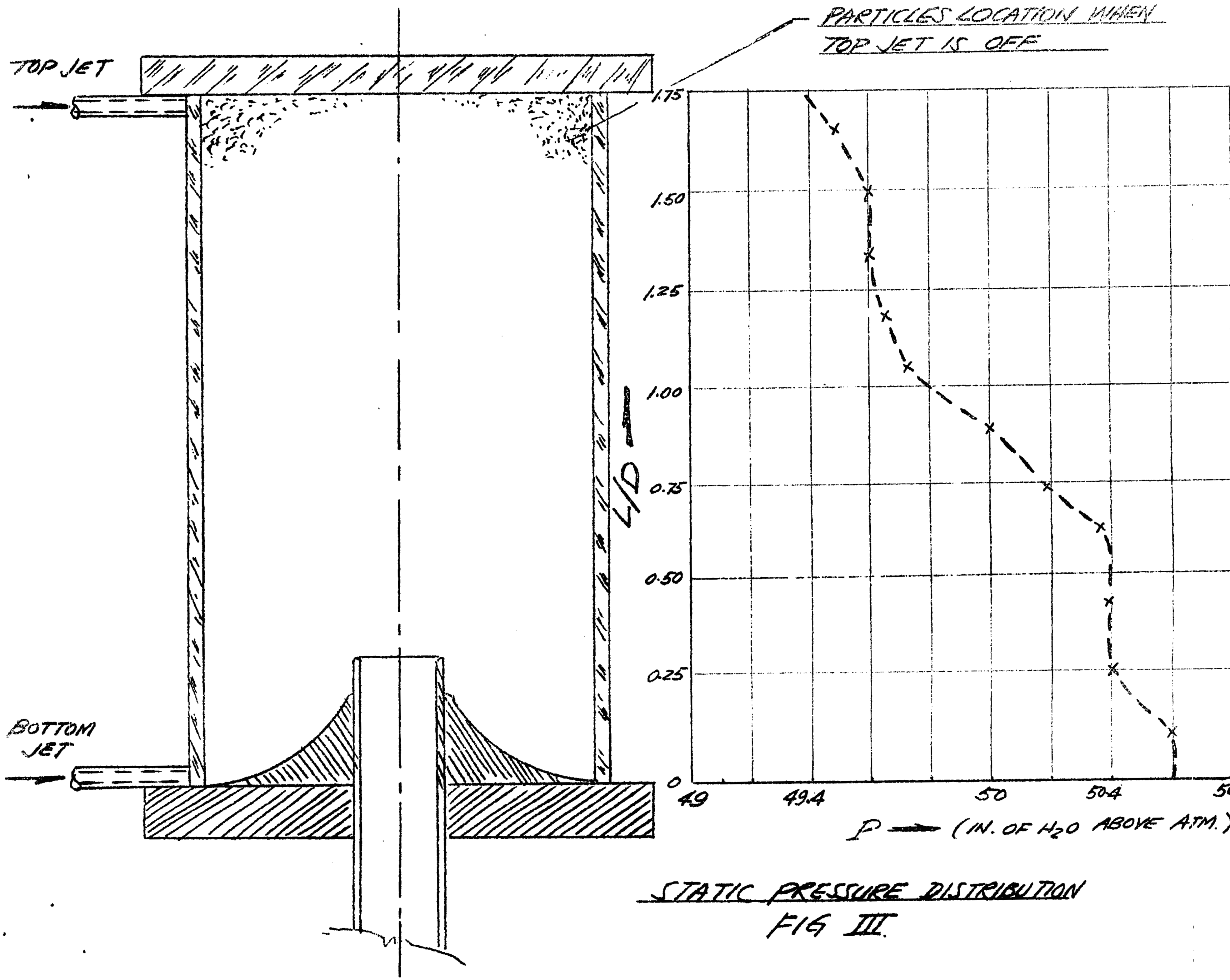
FIG I

CYLINDRICAL GEOMETRY



STATIC PRESSURE DISTRIBUTION

FIG II



STATIC PRESSURE DISTRIBUTION
FIG III.

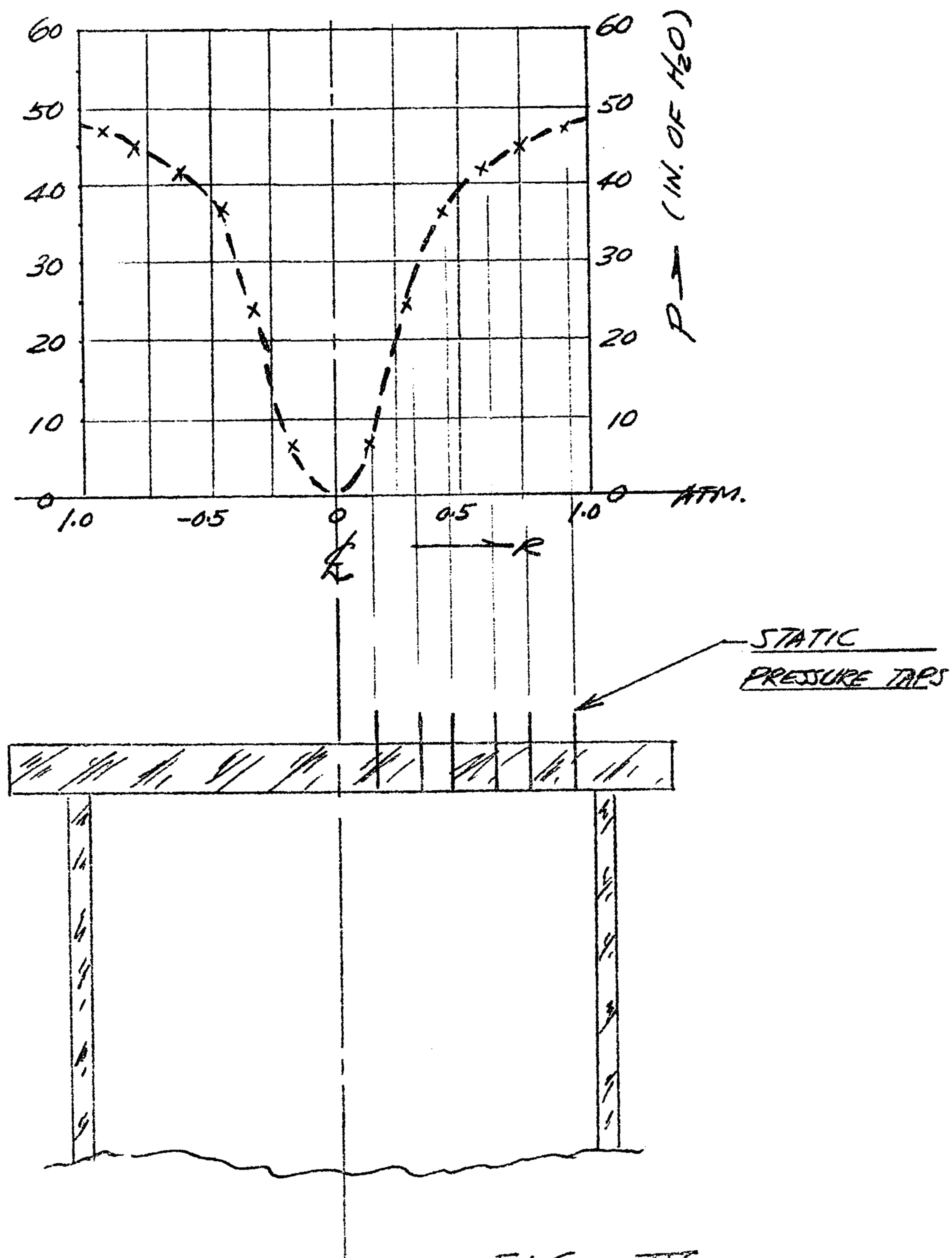


FIG IV

RADIAL STATIC PRESSURE DISTRIBUTION

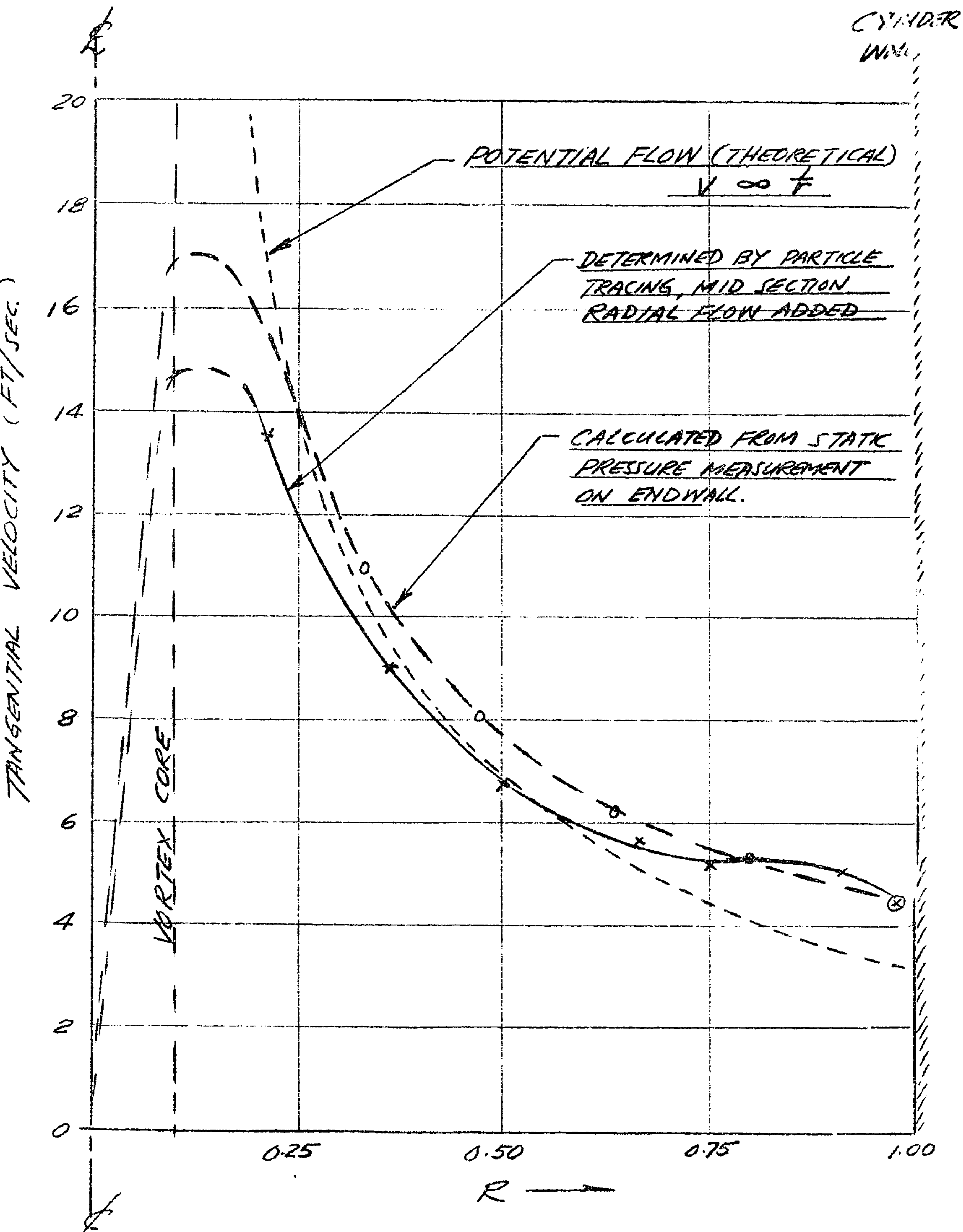


FIG. V

TANGENTIAL VELOCITY DISTRIBUTION

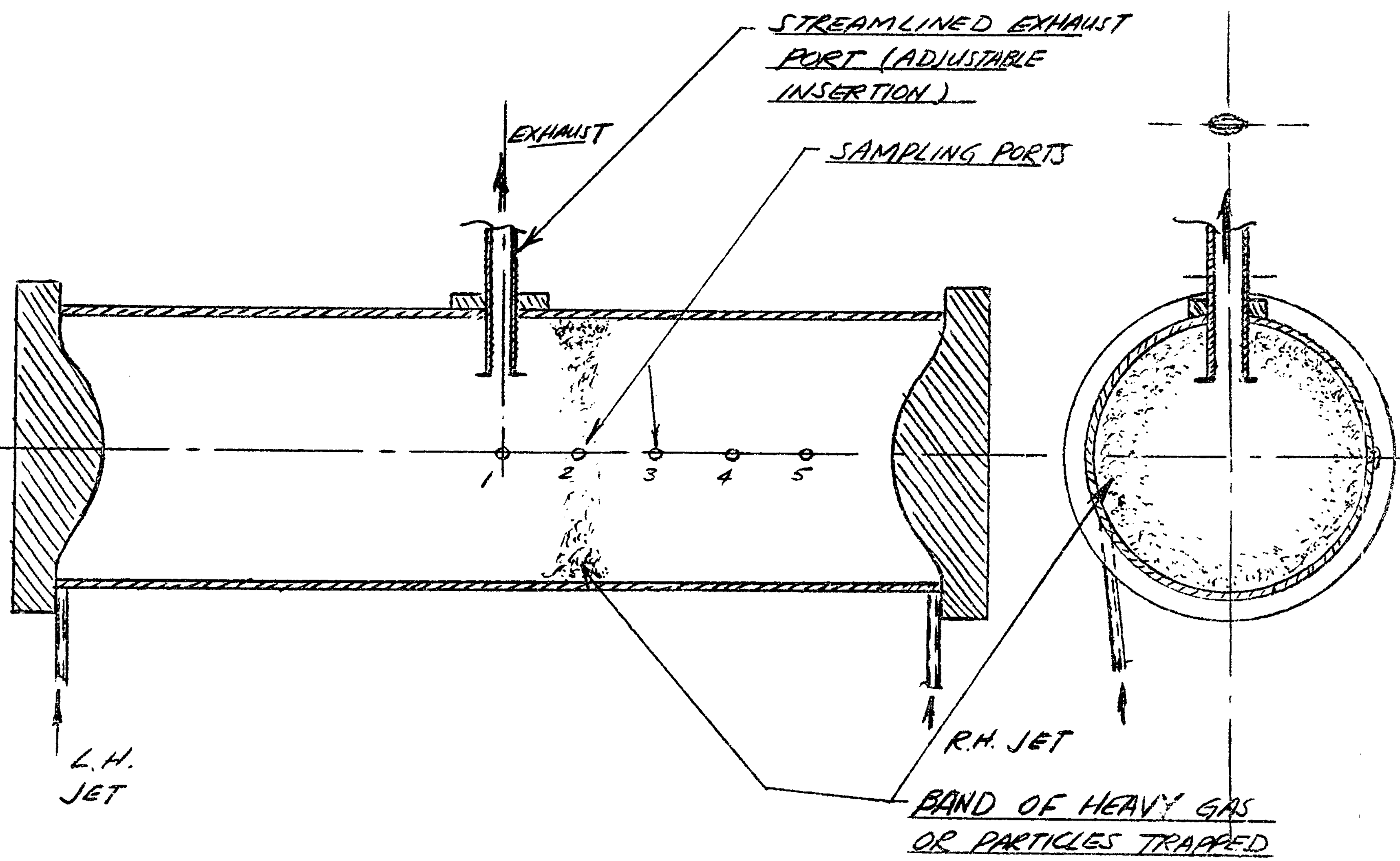
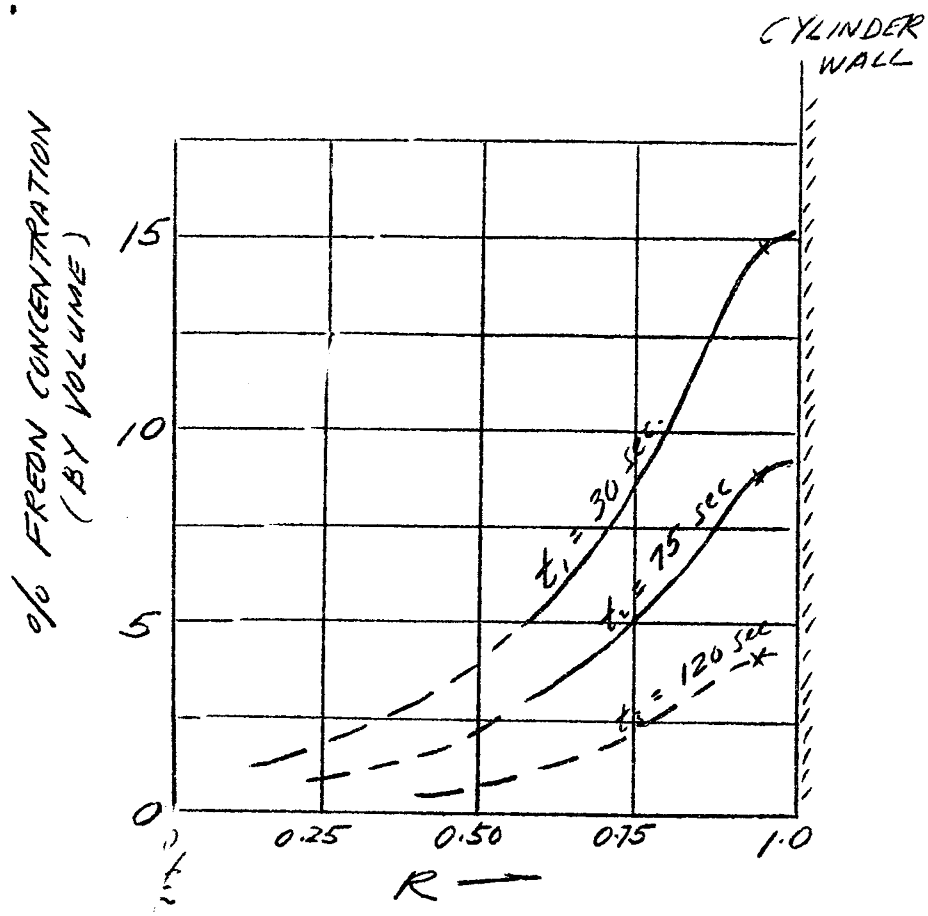


FIG VI

TWO DIMENSIONAL MODEL FOR TOROIDAL GEOMETRY



RADIAL CONCENTRATION DISTRIBUTION OF FREON GAS MEASURED AT DIFFERENT TIME INTERVAL AFTER STARTING AT CONSTANT RATE OF HELIUM FLOW
24 VOLUMES/MIN

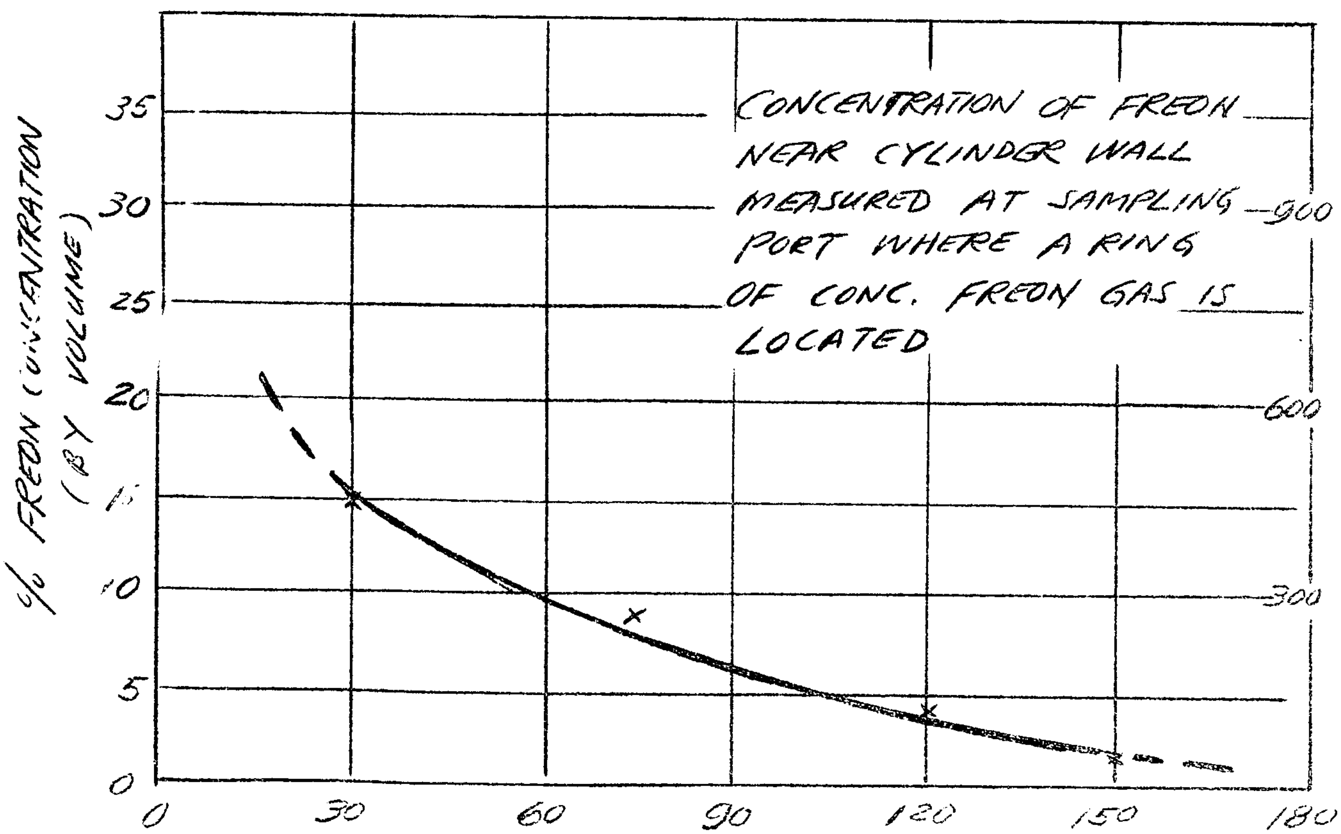


FIG VII TIME (SECONDS)

FREON CONCENTRATION MEASUREMENT DATA